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SCREENING TESTS OF THE ENVIRONMENTAL CRACKING SUSCEPTIBILITY OF LINE-PIPE STEELS UNDER HYDROGEN EMBRITTLING CONDITIONS

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SCREENING TESTS OF THE ENVIRONMENTAL CRACKING SUSCEPTIBILITY OF LINE-PIPE STEELS UNDER HYDROGEN EMBRITTLING CONDITIONS

by

G. J. Biefer*

ABSTRACT

Seven different steel line pipes of recent manufacture, with diameters in the range 30-48 in. (762-1220 mm) and tensile yield strengths in the range 67,000-84,000 psi (462-579 MPa), have been given screening tests of susceptibility to environmental cracking under hydrogen embrittling conditions. Specimens were U-bends, cut circumferentially from the pipe, with the longitudinal weld at the centre. Parent metal hardnesses were in the range Rc 8-17.5 with the weld metal hardnesses being in the range Rc 16-26.

In most of the tests, strongly hydrogen-embrittling conditions were used, the test solution resembling that recommended by the National Association of Corrosion Engineers for testing the susceptibility of steels to hydrogen sulphide cracking

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(3.5% NaCl-0.5% CH_3COOH at R.T., saturated with H_2S). When immersed in this solution, all the steels showed H_2S-cracking failures; four of them within 24 hr on test, all seven steels after 48 hr on test. For steels F, J, R and S, the cracking appeared to have initiated in the heat-affected zone of the weld, whereas for steels A and N, the cracking initiated in the parent metal. For steel P, the cracking tended to initiate in the weld metal. In terms of times-to-failure, six of the steels appeared to be approximately equal in their resistance to H_2S cracking, with the seventh steel, J, being somewhat more resistant. An eighth, spirally-welded steel M, could not be tested because the specimens fractured when an attempt was made to form U-bends.

U-bends of steels F, P and N were tested under comparatively mild hydrogen-embrittling conditions by immersion in 3.5% NaCl solution, while cathodically protected by coupling to zinc. After a one-month immersion, no cracks had initiated.

INTRODUCTION

In 1971, the Physical Metallurgy Division (now designated the "Physical Metallurgy Research Laboratories" (PMRL) undertook the evaluation of a number of commercially available steel line pipes[1]. The pipes chosen were to include some produced by current good practice and also, if obtainable, candidate steels with superior low-temperature mechanical properties for use in the Canadian Arctic.

One of the aspects included in the assessment was to be the environmental cracking (EC)* susceptibility of the steels. However, because EC did not appear to be a very common failure mechanism for line pipes, it was planned to use simple and inexpensive methods and restrict the work to a limited number of rapid screening tests in the environment considered to be of the greatest significance.

As a preliminary, a brief literature survey was made[2] of the EC of line pipe and tubular steels used by the gas and oil industry. This indicated that EC failures could be divided into the three main types which are described below:

1. Stress Corrosion Cracking (SCC)

In recent years, EC failures termed "SCC" by their investigators have been observed on transmission line pipes with

*In this report, the term environmental cracking (environmentally induced stress cracking) is used in a general sense, to include all the mechanisms and associated nomenclature which have been proposed for this phenomenon in its various manifestations; e.g. hydrogen stress cracking, stress corrosion cracking, stress-sorption cracking, caustic embrittlement, hydrogen embrittlement cracking, etc.

apparently normal properties corresponding to the yield strengths currently in use, i.e., 46,000-72,000[3] (317-496 MPa). Such failures originate typically on pipe outer surfaces, and appear to require an aqueous solution containing a sufficiently high concentration of a damaging ionic species, a temperature somewhat above ambient, a sustained tensile stress, and a potential lying within a critical range. The damaging species proposed[3] have included hydroxide, leading to caustic embrittlement cracking[4], carbonate-bicarbonate, and nitrate.

2. Hydrogen Stress Cracking (HSC)

EC failures of transmission line pipes which have been designated "HSC" have been recognized and studied for a longer period than SCC[5]. In common with SCC, HSC failures originate typically on the outer surfaces of transmission line pipes which are under a sustained tensile stress. However, the mechanism is distinctly different from that of SCC. HSC is known to result from the entry of embrittling hydrogen into the metal, maximum susceptibility to cracking being at or near room temperature. The pipes are usually coated, are under cathodic protection, and in contact with ground waters which are considered to be "sweet" (essentially H_2S-free).

It is known that ferritic steels become increasingly susceptible to HSC with increasing tensile strength. In agreement with this, HSC failures are usually observed at localized "hard spots", where the strength level is considerably higher than the nominal strength of the line pipe. According to Groeneveld and Elsea[6], all the documented hard spot failures

have occurred at equivalent tensile strength levels above 177,000 psi (1220 MPa). These workers state that line pipe steels currently in use, with normal properties consistent with yield strengths up to and including 65,000 psi (448 MPa), are not strong enough to be susceptible to HSC. Groeneveld[7] has recently suggested that HSC might only become a service problem for steels with yield strengths above about 115,000 psi (793 MPa).

It is relevant to note that, in laboratory tests at PMRL, steels with yield strengths in the vicinity of 110,000 psi (758 MPa) have shown definite evidence of HSC. The experimental method involved the use of notched, fatigue pre-cracked cantilever specimens broken under a slowly rising load. The test medium was 3.5% NaCl solution at room temperature, cathodic protection being applied by means of a zinc sacrificial electrode. In this work, steels with yield strengths below 110,000 psi (758 MPa) were not extensively examined.

3. Hydrogen Sulphide Cracking

EC failures of transmission line pipes caused by hydrogen sulphide (H_2S) do not appear to have been documented. However, H_2S-cracking is well-known in gas and oil well operations in which tubing, casing and other steel hardware are in contact with "sour" (H_2S-containing) fluids. Tuttle[8] has documented a number of service failures and drawn attention to the need for higher-strength alloys which are resistant to H_2S-cracking, for use in the deep, sour wells which are currently being exploited.

There is general agreement that H_2S-cracking is a particularly severe type of hydrogen stress cracking, with

H_2S acting as a catalytic poison inhibiting the formation of hydrogen molecules at the surface of the steel. This action leads to an increased inward diffusion of embrittling hydrogen atoms.

As in the case of HSC, defined here as occurring in sweet environments, steels become more resistant to H_2S-cracking with decreasing tensile strength. However, the greater severity of H_2S-cracking brings about failures at much lower strength levels. There is a great deal of experience in the petroleum industry to support NACE Standard MR-01-75 (March 1975), which states that carbon and low alloy steels are acceptable for sour service at hardnesses of Rc 22 or less (equivalent to a tensile strength of about 112,000 psi (772 MPa)). However, at least in the laboratory, H_2S-cracking has been observed for steels having much lower strength levels than this. In particular, Carter and Hyatt[9], in an extensive review of the literature, have brought forward evidence that steels with yield strengths less than 50,000 psi (345 MPa) can fail by H_2S-cracking.

4. Research Plan

It was concluded from the information available in 1971 that it would be premature to undertake studies of SCC and that hydrogen-embrittlement EC mechanisms were of greater practical significance. The susceptibility of steels to this kind of attack is increased by such factors as cold work (e.g. at a gouge or scrape), the presence of a sharp notch (e.g. at a dent or fatigue crack), cathodic protection and an unfavourable environment. The latter could consist of a ground water which

is acid, or which contains H_2S or other compounds promoting hydrogen embrittlement. It appeared, therefore, that under an unfavourable combination of circumstances, hydrogen embrittlement might contribute to some of the failures observed in present-day line pipe, even though the steel is intrinsically of good quality.

To accelerate the research, it was decided to perform most of the screening tests on the line pipe steels in an H_2S-containing medium resembling that proposed by the National Association of Corrosion Engineers (NACE) for evaluating the resistance of steels to H_2S cracking. It was assumed that differences in EC behaviour of the steels in this powerful hydrogen embrittling medium would parallel differences which might be shown in the much milder environments usually encountered in transmission pipeline service. Such a parallelism has been demonstrated by McIntyre and Priest[10], who have developed an accelerated EC test in which the test medium is dry H_2S gas.

Two different specimen types had been proposed by NACE Task Group T-1F-9 (Metallic Materials Testing Techniques for Sulphide Corrosion Cracking). After considering their advantages and disadvantages, it was decided to adopt an alternative approach with much lower machine shop costs, namely, the use of U-bend specimens with the mill weld at the centre.

The present report describes the results obtained in tests on eight line-pipe steels obtained by PMRL in the period 1972-1974. The EC testing was exploratory in nature and limited in scope, and was based on specimens from only one length of

pipe supplied by each manufacturer, not necessarily representative of current production and not purchased to a sour service specification. The results are not considered to provide a definitive comparison of the EC susceptibilities of line pipe from the different sources. The names of the manufacturers are, therefore, not divulged and the line pipes are referred to only in terms of a letter code.

EXPERIMENTAL

Line-pipe Steels

A general description of the line-pipe steels tested appears in Table 1. In Tables 2 and 3, the chemical compositions and some mechanical and impact properties of the steels, as supplied by the manufacturers, are presented.

Specimens

The specimen dimensions were 10 in. long x 1 in. wide (254 x 25.4 mm) with the thickness being that of the pipe wall. For longitudinal welded pipes, specimens were cut so that the length was circumferential with respect to the line pipe axis, with the weld at the centre. For spiral-welded line-pipe M, the specimens were cut so that the length was at right angles to the direction of the weld. Two 3/8-in. (9.5 mm) diameter holes were drilled through each specimen, one near each end. The curved surfaces of the specimens were left in the as-received condition, i.e., painted on the inner surface but not on the outer surface, and unnotched.

In preparation for testing, each specimen was bent (with the pipe outer surface on the tension side) in a guided bend-test rig, using a hydraulic plunger to force it into a 1-1/2 in. (38 mm) radius die (Fig. 1). After removal from the die, the partially bent specimen was further bent in a vise until the two opposing arms were very nearly parallel to each other. The specimen was then held in this U-bend configuration by inserting a Type 316 stainless steel tie-rod through the holes and tightening down the end nuts. Rubber tubing and washers were used to prevent any electrical connection between the stainless steel and the line-pipe steel. A typical U-bend specimen is shown in Fig. 2.

Steel S had a wall thickness of 1.25 in. (32 mm), too great to permit the production of U-bends of the same radius as the other steels. The concave surfaces of the unbent specimens were, therefore, milled until the wall thickness was about 0.59 in. (15 mm). The U-bends were then prepared in the usual way.

Methods in H_2S Tests

The tests were performed at room temperature in a 3.5% NaCl - 0.5% acetic acid solution which was saturated with H_2S, using the apparatus shown schematically in Fig. 3.

For each test, ten litres of the standard solution was saturated by bubbling H_2S through it at a rate of about 50 ml/min for a period of 16 hours. This solution was then transferred to the 20-litre test vessel, in which the degreased U-bends (usually 4 in number) had been previously suspended from

the lucite lid such that their bent portions would be immersed in the aqueous phase (ratio, solution volume/metal area ≒ 20 ml/cm^2). H_2S was bubbled through the test vessel at 50 ml/min throughout the tests and small samples of the solution were withdrawn at intervals for the determination of pH.

The U-bends were viewed at intervals through the glass walls of the test vessel to see whether cracking had occurred. At the conclusion of a test period lasting a maximum of one week, the H_2S gas was shut off and the system was thoroughly purged with N_2 before opening the test vessel to remove the specimens.

Methods in NaCl Solution

Twenty litres of 3.5% NaCl solution were poured into a wide-mouthed jar. This permitted immersion of the weld-containing half of each specimen, with support from above. Each of the four specimens that was tested simultaneously was provided with its own sacrificial zinc anode.

The only test performed lasted for a period of one month.

RESULTS

1. Tests in H_2S Solution

The results obtained in the U-bend tests in H_2S-saturated solution are summarized in Table 4. Where the time to failure shows a range, the lower figure is the longest period at which the specimen was observed to be still uncracked,

whereas the higher figure is the time at which cracking was first definitely observed. The term "NC" signifies that no cracking was visible through the glass walls of the reactor at the conclusion of the test. (Two of the J specimens denoted "NC" were subsequently found to have shallow fissures in the central part of the HAZ which might possibly have indicated cracking; it would have taken metallographic sectioning to determine this.)

After completion of each test, the specimens were rinsed in distilled water then thoroughly dried and their surfaces examined with the help of a low-power stereomicroscope. As much as possible, an attempt was made to determine within which microstructure the crack had initiated, and this is indicated in Table 4. Depths of the cracks are also indicated; by definition, "deep" cracks are those which extended more than halfway through the specimen thickness while "shallow" cracks did not attain this minimum depth within the duration of the test. In practice, most of the deep cracks extended very nearly through the specimen thickness and the shallow cracks were less than 1/8 in. (3 mm) deep. Photographs of the specimens are reproduced in Figs. 4 to 10.

Table 4 also presents the results of Rockwell C hardness tests, carried out on the machined edge of a typical U-bend of each steel after the tests. The parent metal values were obtained at points two or more inches (50 or more mm) from the weld. The weld metal values were obtained on the weld centre line at locations well removed from the surface. Table 5 presents the results of pH measurements of the test solutions, made at different stages of the tests.

2. Tests in 3.5% NaCl Solution

Four U-bends were put on test, two of steel P and one of each of steels F and N. At the beginning of the test, the zinc anodes gave a specimen potential of about -1.05 volts (SCE) and solution pH was about 6. At the conclusion of the test, after the specimens had been immersed for one month, potentials were -1.01 to -1.02 volts and the solution pH was 7.2. A thorough post-test examination of the surfaces of all four specimens did not reveal any cracking.

3. H_2S Crack Morphology

At the conclusion of tests, many of the U-bends showed gaping cracks with corroded surfaces which obviously did not warrant examination. However, a few of the specimens showed fine cracks which had not opened up and these were investigated to a limited extent.

For U-bend S-3, Fig. 11 shows the crack initiation in the HAZ, with subsequent propagation into the parent metal. Fig. 12 shows the crack tip as it is related to the parent metal microstructure. Both intergranular and transgranular crack paths can be seen, with some branching.

For U-bend F-2, an examination of the EC surfaces, using the scanning electron microscope, showed both intergranular and cleavage crack paths.

4. Steel M

This line pipe steel differed from the rest in that it was spirally welded. Two attempts to form U-bends, using

the usual methods, failed because of specimen fracture at the HAZ when the angle between the two arms was about 140°. For a third specimen, the weld bead was ground to the level of the adjacent metal prior to the forming operation and a U-bend was successfully produced. However, this non-standard U-bend was not tested.

A photograph of unbent specimens of steels F, J and M is reproduced in Fig. 13. This shows the weld bead profiles. The differences in profile do not seem to favour the cracking of steel M upon bending in air as contrasted with the other two.

In an attempt to provide an explanation of the cracking, a Tukon micro-hardness traverse (1.0 kg load, 10.25 mm objective), using the Knoop indenter, was taken across the weld and in the immediately adjoining parent metal. It was found that the parent metal showed hardnesses equivalent to Rc 20-23, and the weld metal Rc 20-21. In the HAZ, values were Rc 19-30.

5. Hardness of HAZ of Steel F

Steel F was to some extent regarded as a standard material. It was, therefore, decided to perform hardness measurements on the HAZ, using the Tukon micro-hardness tester with the Knoop indenter as described above.

On U-bend F-2, determinations within the recrystallized region of the HAZ gave equivalent hardnesses of Rc 23-31, the average of fourteen readings being Rc 26. In the parent metal about 0.12 in. (3 mm) from the weld fusion line, equivalent hardnesses were Rc 22-23.

On another unbent circumferential section cut from pipe F, parent metal at a point on the edge well removed from the weld had equivalent hardnesses of Rc 10-11.5. This was in good agreement with the Rc determinations obtained for parent metal in the tested U-bends (Table 4). It appeared, therefore, that the significantly higher hardness values obtained in the parent metal of U-bends, just outside the HAZ, must have been due to the intense cold working of the steel during the bending.

6. Strain in U-bend in Steel R

It was considered important to gain at least an approximate idea of the amount of strain in the metal after formation of a U-bend. For an unbent specimen of steel R, a diamond tip was used to produce light, parallel scratches, about 0.06 in. (1.5 mm) apart, and oriented in the direction of the weld. The scratches extended from the centre of the weld across the HAZ to a point in the parent metal more than an inch (25 mm) from the weld. This included the entire region within which H_2S cracking of U-bends had been observed.

A U-bend was formed in the usual way, after which the altered distance between the scratches was measured, at a line running along the centre of the specimen length. This permitted calculation of the percentage of strain at different locations in the U-bend, the results being shown in Table 6.

DISCUSSION

1. Tests in H_2S Solution

It is known that susceptibility of steels to hydrogen embrittlement cracking is increased by both higher hardness and greater cold work. With respect to the U-bends, analysis of the factors involved would be complex. Prior to forming the U-bend, the microstructures in the parent metal, the HAZ, and the weld metal will usually show different hardnesses. After forming the U-bend, the surface strain will vary with distance from the weld, apparently being at its maximum in the HAZ because of geometrical considerations. Hence hardness at any one location is likely to be altered according to the strain undergone and the cold-working properties of the microstructure at that location.

A determination of the region in which cracks initiated, based on a post-test examination of the U-bend surfaces, cannot always be conclusive. However, for each steel, the cracking appeared to initiate in a characteristic region, presumably where the combination of hardness and strain gave maximum susceptibility to H_2S-cracking. For steels F, J, S and R, cracks tended to initiate at the HAZ; for steels A and N, cracks initiated in parent metal, whereas for steel P, the cracking tended to initiate in the weld.

It was concluded that it would be necessary to perform separate EC tests on each of the microstructures involved - parent, HAZ, and weld metal - in order to explain the trends observed in the measurements.

In attempting to compare the steels, the time-to-failure data of Fig. 4 are difficult to interpret because of the unavoidable gaps which occur when visual observations must be relied on. A retabulation as shown in Fig. 7 facilitates interpretation of the data which, however, did not yield a very well defined result. It can only be said that six of the steels were approximately equal in their resistances to EC in a strongly hydrogen-embrittling medium. The only exception was steel J, which appeared to be somewhat more resistant than the others.

The use of more refined techniques - e.g. quantitative measurement of times-to-failure, two-point bending of specimens to preselected strains - might have demonstrated differences among the steels. However, with the resources available, such approaches had to be ruled out.

2. Tests in 3.5% NaCl Solution

The few tests of U-bends in 3.5% NaCl, cathodically protected by zinc, did not show any EC, even after a test period of one month. It is evident that these conditions are not sufficiently hydrogen-embrittling to be useful in this type of screening test.

SUMMARY

A number of steel line pipes of recent manufacture, with diameters in the range 30-48 in. (762-1220 mm) and tensile yield strengths in the range 67,000-84,000 psi (462-579 MPa),

have been given screening tests of susceptibility to environmental cracking under hydrogen embrittling conditions. The specimens were U-bends, cut circumferentially from the pipe so that the longitudinal weld was at the centre. Parent metal hardnesses were in the range Rc 8 - 17.5 with the weld metal hardnesses being in the range Rc 16-26. The solution used in most of the tests was 3.5% NaCl-0.5% acetic acid, saturated with H_2S, at room temperature. The following results were obtained.

1. U-bends of each of the seven different line-pipe steels showed H_2S cracking; four of the steels within 24 hr, all of them within 48 hr.

2. Steel J appeared to be more resistant to H_2S cracking than the other six steels, which were more or less equivalent in their behaviour.

3. For each of the steels, the H_2S cracking tended to initiate in a characteristic microstructure; steels F, J, S and R in the HAZ, steels A and N in the parent metal, and steel P in the weld.

4. Spirally welded steel M could not be tested because the specimens fractured in air when an attempt was made to form U-bends.

5. U-bends of steels P, F and N were tested in 3.5% NaCl at room temperature, cathodically protected by zinc sacrificial anodes. After a test period of one month, no cracking was observed.

CONCLUSIONS

1. The screening tests on U-bends containing a mill weld showed that all seven line-pipe steels tested are subject to EC failures by hydrogen embrittlement under extreme conditions of high H_2S concentration and heavy cold working.

2. The results of the U-bend tests indicated that the steels had similar resistances to EC by hydrogen embrittlement with the possible exception of steel J, which may have been somewhat more resistant.

3. A more quantitative assessment of the steels would be obtained by the use of more refined methods, and/or the performance of separate EC tests on each of the relevant microstructures (parent, HAZ, weld).

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Table 1. General Description of the Line-Pipe Steels

Code Letter	Size, in.* (o.d. x wall thickness)	API Specification or Designation	Other Details
A	30 x 0.375	Experimental	As-rolled and aged 1 hr at 1300°F (700°C)
F	36 x 0.518	5LX-X65	Controlled-rolled
J	48 x 0.562	5LX-X65	Controlled-rolled
M	42 x 0.390	5LX-X70	Controlled-rolled Spiral weld
N	42 x 0.420	5LX-X65	Controlled-rolled
P	48 x 0.720	5LX-X70	Controlled-rolled
S	48 x 1.25	5LX-X65	Quenched and tempered
R	48 x 0.720	5LX-X70	Controlled-rolled

* inches x 25.4 = mm

Table 2. Manufacturer's Analysis of Line-Pipe Steels

Element, %	A	F	J	M	N	P	S	R
C	0.04	0.16	0.11	0.06	0.07	0.10	0.10	0.10
Mn	0.44	1.25	1.28	1.65	1.38	1.47	1.30	1.48
P	0.010	0.008	0.014	0.012	0.010	0.017	0.008	0.014
S	0.015	0.009	0.008	0.014	0.009	0.004	0.003	0.002
Al	--	--	0.033	--	0.050	0.039	0.034	0.033
Nb	0.04	0.047	0.04	0.054	0.140	0.04	0.03	0.05
Si	0.27	0.35	0.25	0.04	--	0.27	0.30	0.25
Cu	1.22	--	--	0.19	--	0.28	--	0.31
Ni	0.91	--	--	0.19	--	0.28	0.45	0.32
Cr	0.67	--	--	0.09	--	--	--	--
Mo	0.20	--	--	0.24	--	--	0.08	--
Sn	--	--	--	0.014	--	--	--	--
V	--	--	0.05	--	--	0.09	--	0.1
N	--	--	0.005	--	--	--	--	--

Table 3. Mechanical Properties as Supplied by Manufacturers*

Steel	Y.S. (ksi)	UTS (ksi)	% Elong. (2 in.)	Charpy Test	Battelle DWTT
A	84	87	29	--	80% shear at -10°F (-23°C)
F	67.2	91.8	32	2/3 Charpy, 42 ft-lb, 97% shear at 25°F (-4°C)	1,613 ft lb, 85% shear at +25°F (-4°C)
J	66.7	84.8	37	38 ft lb, 100% shear at -20°F (-29°C)	80% shear at -20°F (-29°C)
M	72.3	91.3	32	--	3,335 ft lb, 100% shear at 25°F (-4°C)
N	67	81.1	38	2/3 Charpy, 66 ft-lb, 88% shear at 25°F (-4°C)	2,718 ft lb, 100% shear at 25°F (-4°C)
P	77.2	95.3	36	45 ft lb at -100°F (-73°C)	886 ft lb, 37% shear at -76°F (-60°C)
S	72.1	86.2	58	217 ft lb, 100% shear at -20°F (-29°C)	100% shear at -20°F (-29°C)
R	74.7	88.5	41	86 ft lb at -100°F (-73°C)	1,754 ft lb, 62% shear at -76°F (-60°C)

* ksi x 6.89 = MPa
in. x 25.4 = mm
ft lb x 1.356 = joules

Table 4. Behaviour of Line Pipe Steels in H_2S-saturated Solution, 3.5% NaCl - 0.5% Acetic Acid, at Room Temperature

Steel	Specimen Number	Rc Hardness parent	Rc Hardness weld	Time to show cracking, hr	Description
A	A-1	8.5-11.5	17-20.5	18-40	Deep crack in parent metal
	A-2	--	--	18-40	" "
F	F-1	--	--	48-49	Deep crack in one HAZ. Shallow crack in the other HAZ.
	F-2	9-11	--	<24	Deep crack in HAZ propagating to parent metal.
	F-3	8.5-12	16-17.5	<24	Deep crack in HAZ
	F-4	--	--	49-65	Deep crack in HAZ
J	J-1	--	--	NC, 168	Shallow fissure in HAZ
	J-2	--	--	46-66	Deep crack in HAZ
	J-3	--	--	42-46	Deep crack in HAZ
	J-4	8	16.5-23	NC, 168	Shallow fissure in HAZ
N	N-1	8	16-23.5	<18.5	Deep crack in parent metal
	N-2	--	--	18.5-23	" "
	N-3	--	--	42.5-66.5	" "
	N-4	--	--	18.5-23	
P	P-1	15-17.5	21-24	<22.2	Deep crack in weld
	P-2	--	--	NC, 168	No cracking visible
	P-3	--	--	22-35.5	Deep crack in weld
	P-4	--	--	22-35.5	Shallow crack mostly in weld, partly in HAZ.

Table 4 cont'd.

Table 4 (cont'd)

Steel	Specimen Number	Rc Hardness parent	Rc Hardness weld	Time to show cracking, hr	Description
S	S-1	9-10	19-21.5	<21	Deep crack in HAZ
	S-2	--	--	33-45	Deep crack mostly in weld near fusion line, partly in HAZ.
	S-3	--	--	49.5-56	Shallow crack in HAZ
	S-4	--	--	33-45	Shallow crack in HAZ
R	R-1	12-14.5	20-26	23.5-29	Deep crack in HAZ
	R-2	--	--	23.5-29	Deep crack in HAZ
	R-3	--	--	NC, 182	No cracking visible
	R-4	--	--	49-53	Deep crack in parent metal

Table 5. pH Values Recorded during Tests in H_2S-saturated 3.5% NaCl - 0.5% CH_3COOH Solutions

Elapsed Time of Test, hr	Steel A	Steel F	Steel J	Steel N	Steel P	Steel S	Steel R
0	2.80	2.80	2.84	2.90	2.76	2.80	3.51
16	2.85	--	--	--	--	--	--
18	--	--	2.89	3.10	--	--	--
22	--	--	--	--	2.95	--	--
24	--	3.20	--	--	--	--	3.96
34	--	--	--	--	--	2.80	--
40	2.93	--	--	--	--	--	--
48	--	3.25	--	--	--	--	3.87
67	--	--	--	--	--	2.80	--
68.5	--	--	--	3.30	--	--	--
93.5	--	--	--	--	3.25	--	--
122.5	--	--	--	--	2.40	--	--
156	--	--	--	--	--	--	4.25
162	--	--	4.05	--	--	--	--
168	--	--	--	--	2.38	--	--
182	--	--	--	--	--	--	4.27

Table 6. Strain in U-Bend of Steel R

Striation Number	Per cent Strain	Remarks
1	22.5	At the weld centre line.
2	17.2	
3	16.1	
4	23.1	
5	18.9	
6	26.6	
7	22.7	In the weld, adjacent to the fusion line.
8	59.6	Across the weld toe; includes the spread caused by cracking at the toe.
9	60.8	In the HAZ.
10	52.3	
11	43.0	In the parent metal.
12	33.6	
13	24.8	
14	23.3	
15	21.7	
16	22.1	
17	18.7	
18	18.4	
19	22.3	
20	23.8	
21	20.9	
22	23.3	
23	28.0	
24	25.7	
25	24.5	

Table 7. Time-to-Failure Data from Table 4

Time on Test	Fraction of Specimens Uncracked for Steel						
	A	F	J	N	P	S	R
24 hr	2/2?	2/4	4/4	1/4	3/4?	3/4	4/4?
30 hr	2/2?	2/4	4/4	1/4	3/4?	3/4	2/4
36 hr	2/2?	2/4	4/4	1/4	1/4	3/4?	2/4
42 hr	0/2	2/4	4/4	1/4	1/4	1/4	2/4
48 hr	0/2	2/4	3/4?	1/4?	1/4	0/4	1/4
60 hr	0/2	1/4?	3/4?	1/4?	1/4	0/4	1/4
72 hr	0/2	0/4	2/4	0/4	1/4	0/4	1/4
1 week	0/2	0/4	2/4	0/4	1/4	0/4	1/4

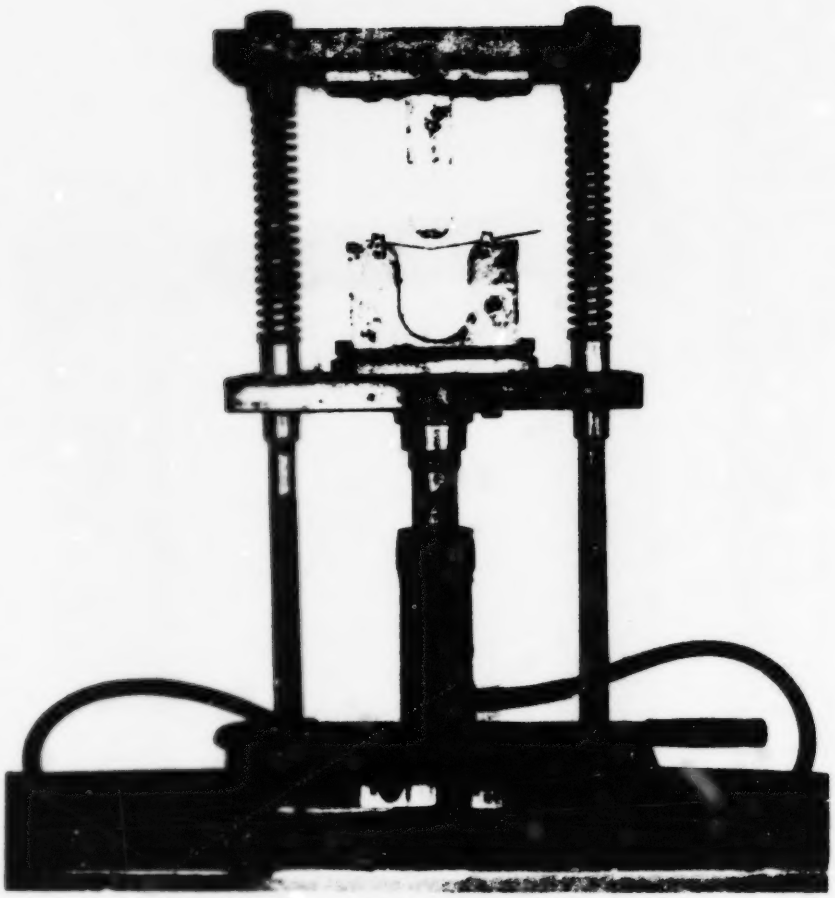

Fig. 1. Hydraulic Plunger being used to prepare a U-bend specimen.

Fig. 2. U-bend specimen of line-pipe steel ready for testing.

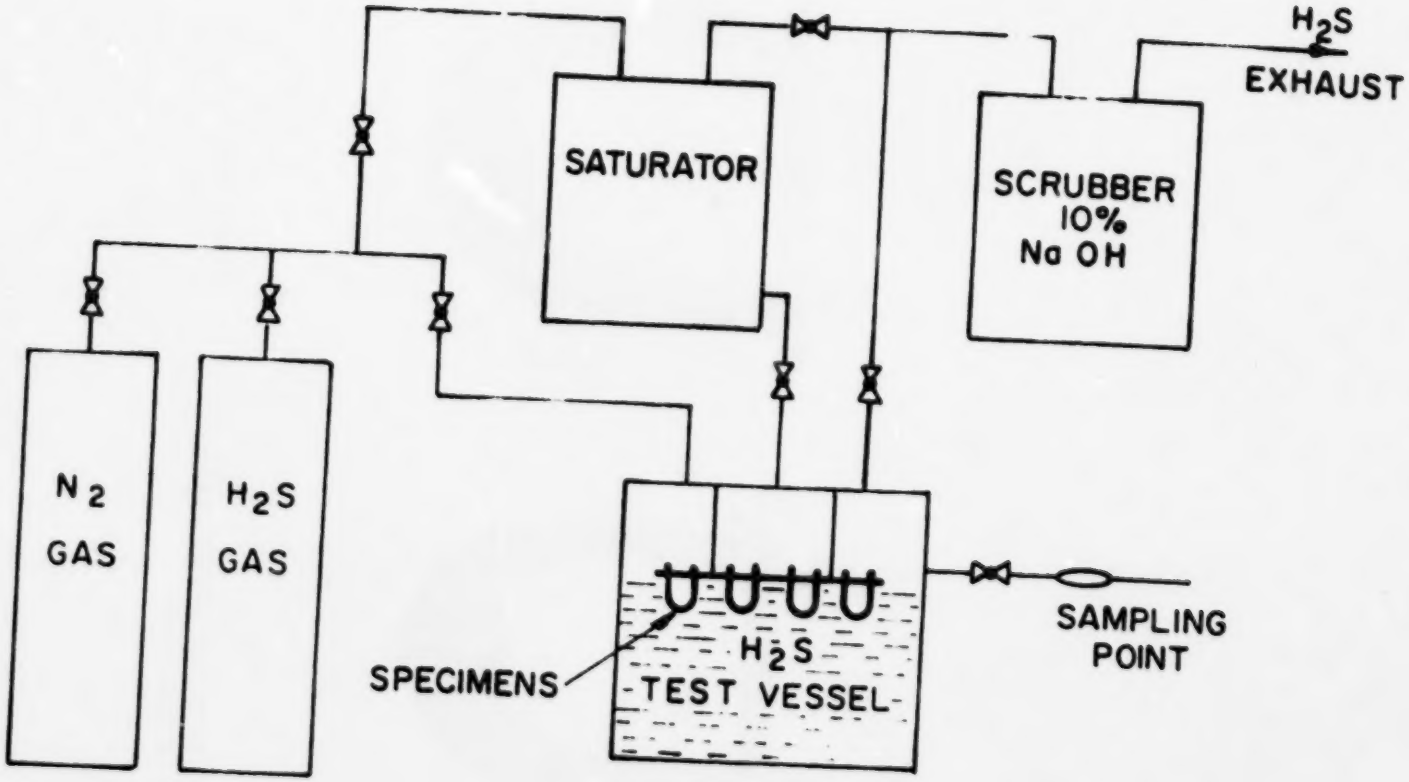

Fig. 3. Schematic diagram of the equipment used for U-bend tests in H_2S-saturated solutions.

"A"

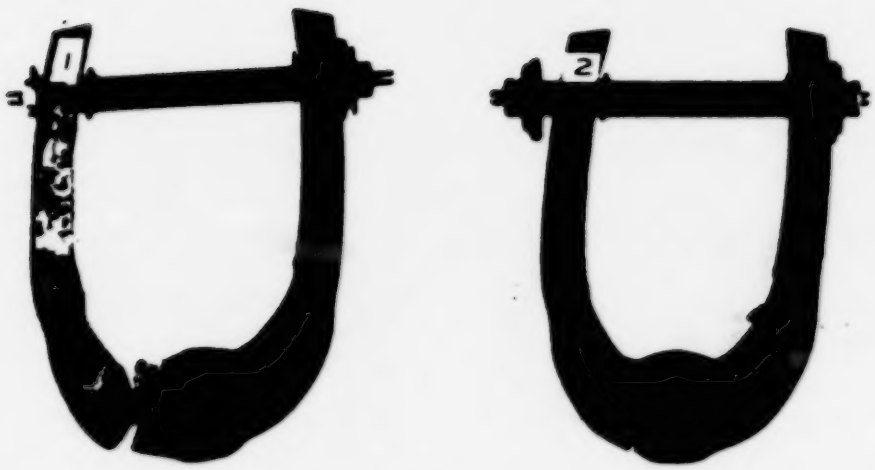

Fig. 4. U-bend specimens of line-pipe steel A after testing in 3.5% NaCl - 0.5% acetic acid saturated with H_2S. X 1/2

"F"

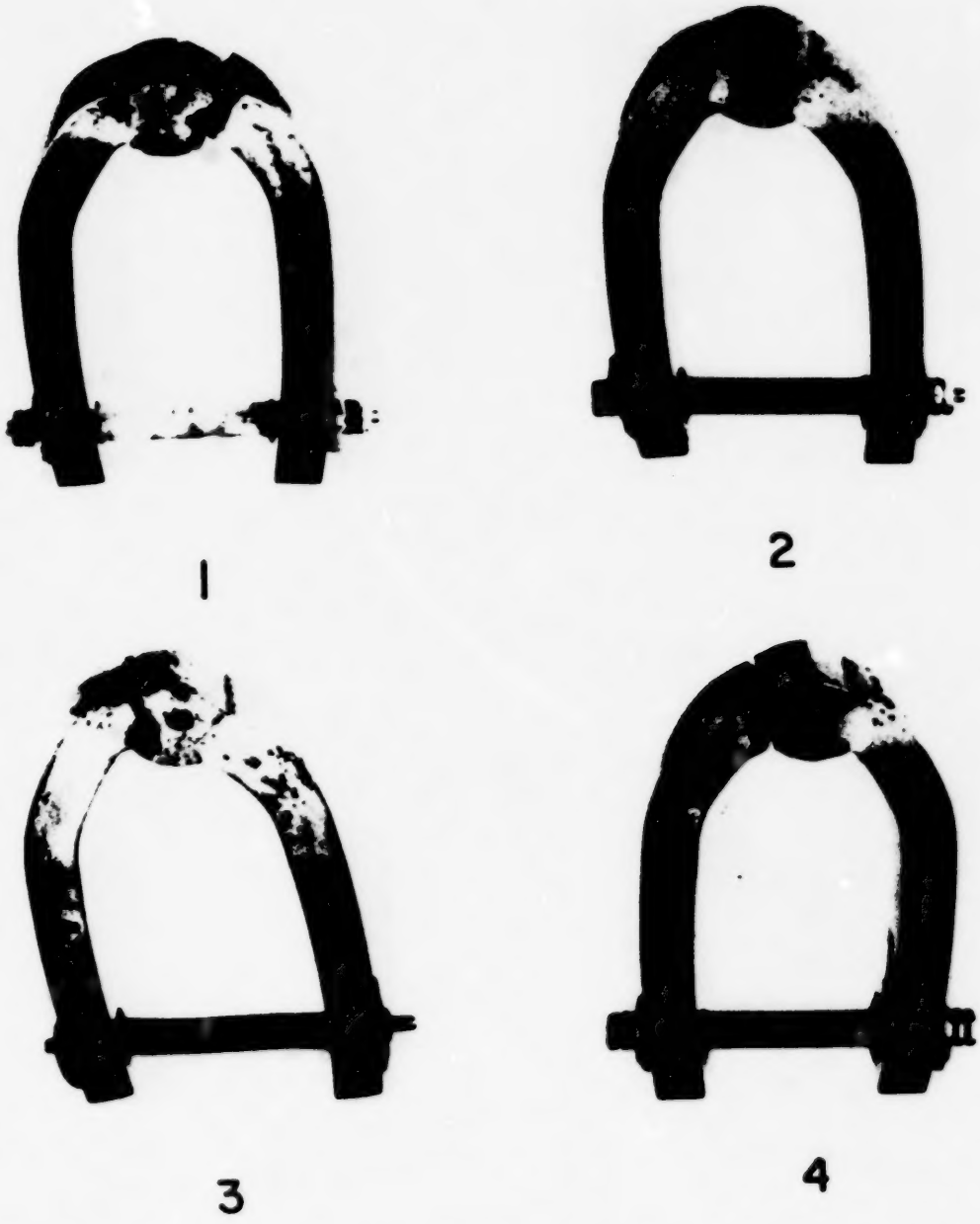

Fig. 5. U-bend specimens of line-pipe steel F after testing in 3.5% NaCl - 0.5% acetic acid saturated with H_2S.

X 1/2

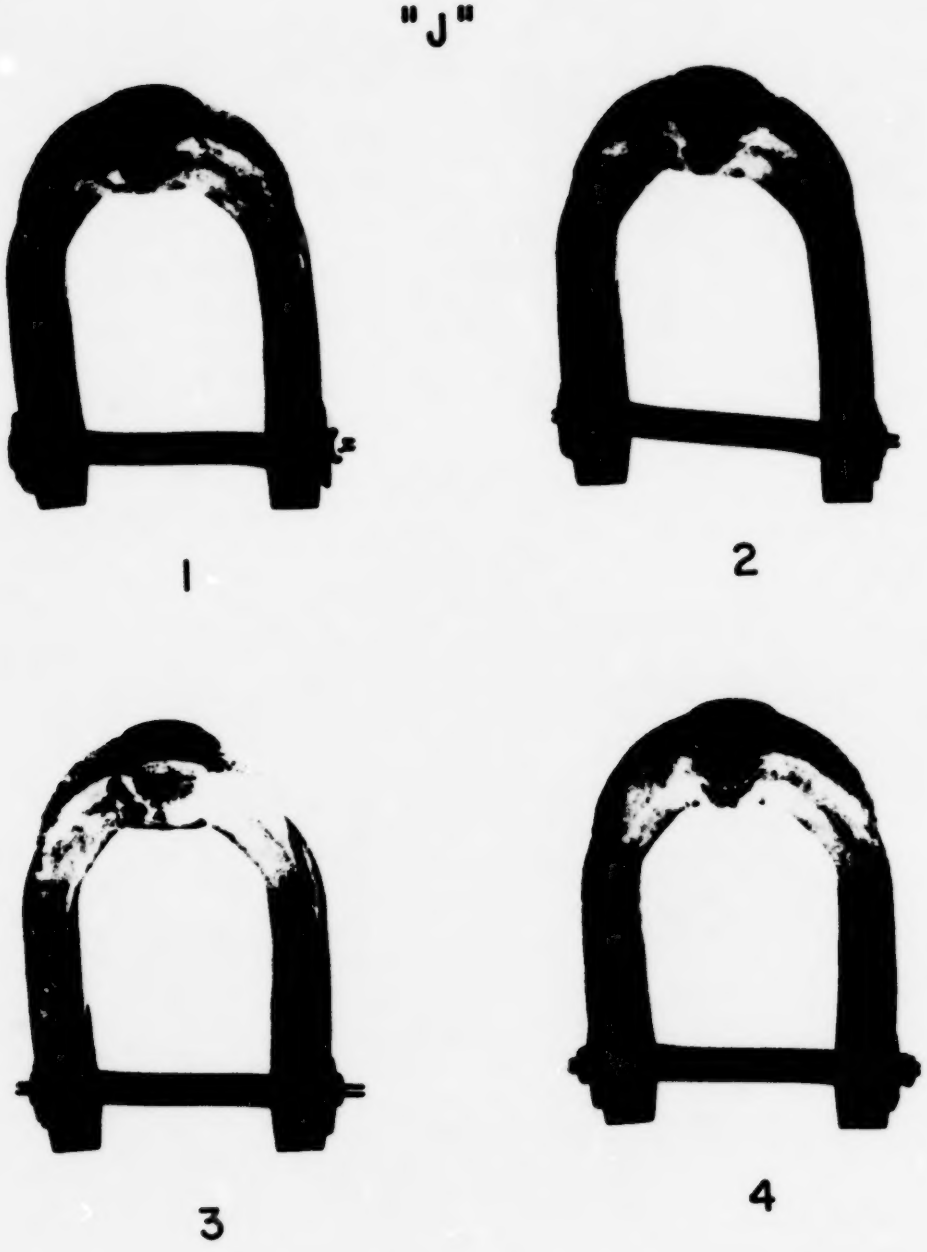

Fig. 6. U-bend specimens of line-pipe steel J after testing in 3.5% NaCl - 0.5% acetic acid saturated with H_2S.

X 1/2

"N"

Fig. 7. U-bend specimens of line-pipe steel N after testing in 3.5% NaCl - 0.5% acetic acid saturated with H_2S.

X 1/2

Fig. 8. U-bend specimens of line-pipe steel P after testing in 3.5% NaCl - 0.5% acetic acid saturated with H_2S.

X 1/2

" S "

Fig. 9. U-bend specimens of line-pipe steel S after testing in 3.5% NaCl - 0.5% acetic acid saturated with H_2S.

X 1/2

"R"

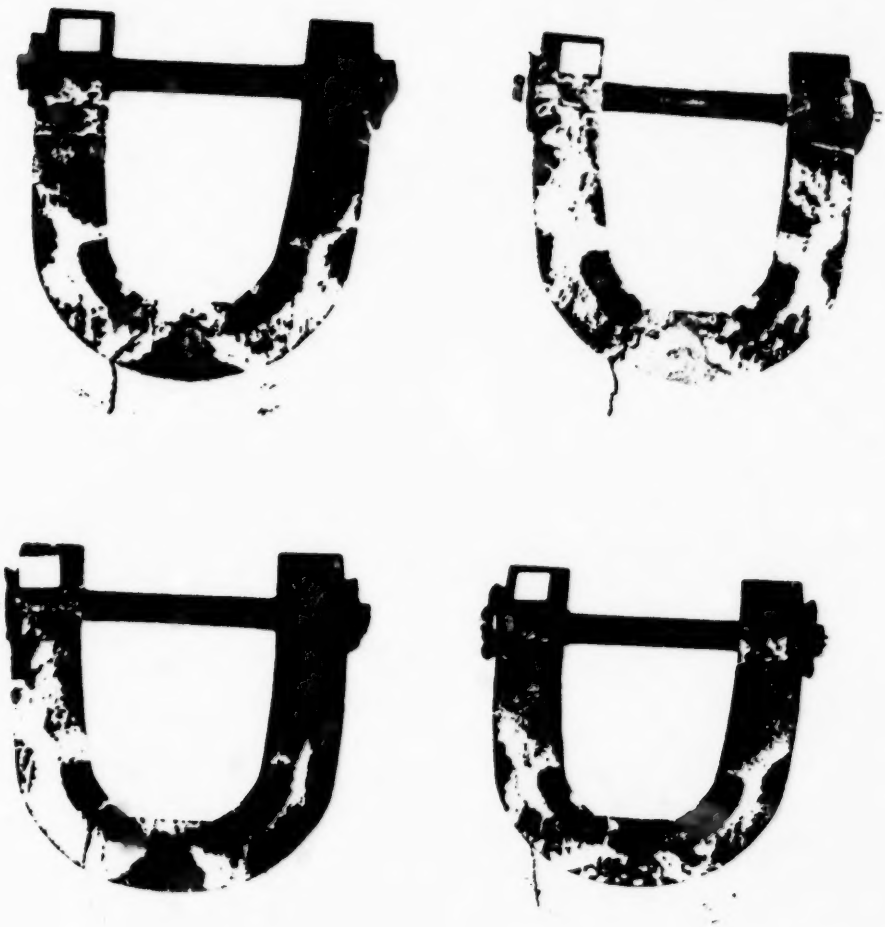

Fig. 10. U-bend specimens of line-pipe steel R after testing in 3.5% NaCl - 0.5% acetic acid saturated with H_2S.

X 1/2

Fig. 11. Initiation of H_2S crack in the HAZ of U-bend specimen S-3.

X 100

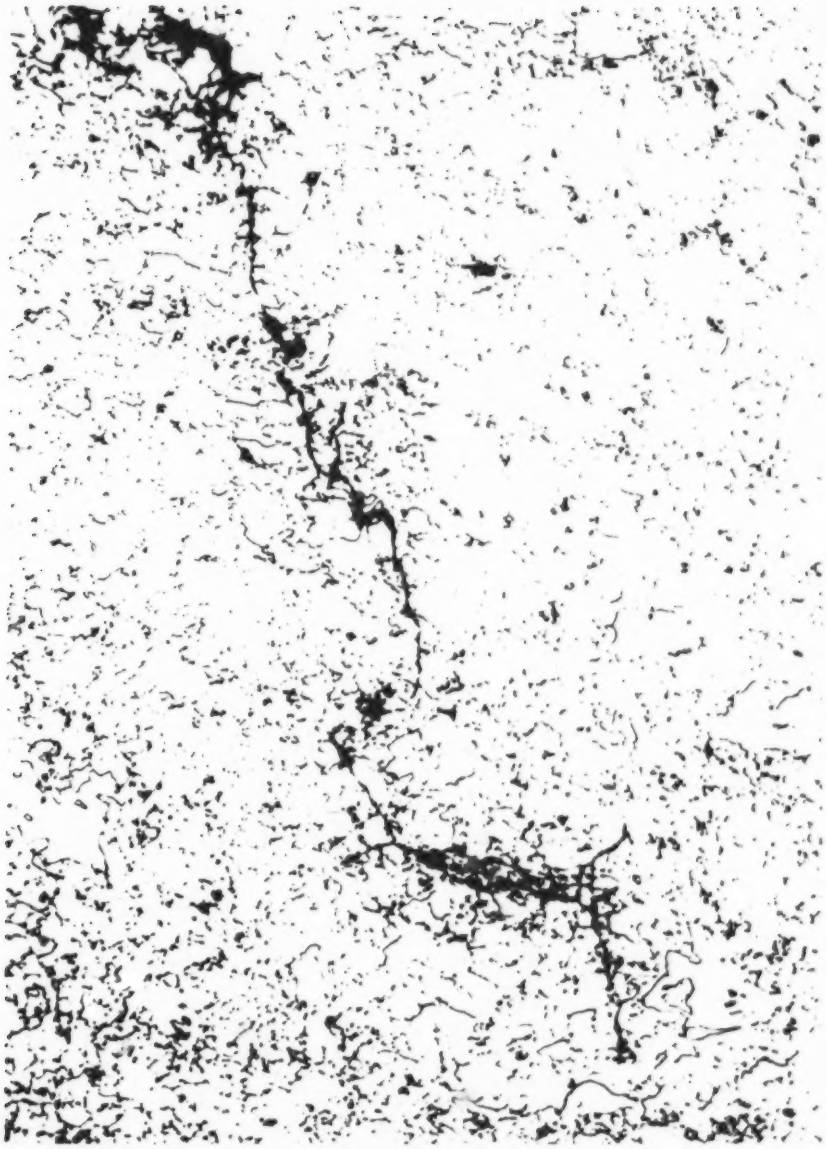

Fig. 12. H_2S crack tip in parent metal of U-bend specimen S-3.
X 500

Fig. 13. U-bend specimens of three steels prior to bending. (Full scale).

POOR

QUALITY

ORIGINAL